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## Flight Mechanics of the Wright Aircraft 1903-1912

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## Abstract

Perhaps the most curious aspect of the Wright Brothers' program to invent and commercialize the airplane is their decision in 1900 to use their novel canard configuration, and to persist with that geometry until 1910 despite the known deficiency that the aircraft were unstable in pitch. The reasons for their initial choice are well-known. Several studies in the past twenty years have proven beyond doubt that the Wrights did not intentionally make their canards unstable. The pitch instability of their machine was an unwitting byproduct of their design chosen partly out of fear of the conventional design and partly (they reasoned) for more positive control. With their great emphasis on control, the Wrights were able to develop a successful aircraft, albeit difficult to fly additionally because the 1903 aircraft also possessed a fast spiral instability. A canard design is not necessarily unstable, but owing chiefly to their airfoil, and an unfortunate fore-and-aft mass distribution, the Wright canards were all unstable. Though easier to fly, their 1909 aircraft was more unstable than the famous 1903 *Flyer* and the Brothers did not have a stable design until they finally adopted a conventional aft horizontal tail in 1910. Successful control of the canard aircraft depended heavily on large damping-in-pitch. The purpose of this paper is to apply modern analysis of flight mechanics to trace the detailed flying characteristics of their powered aircraft from 1903 to 1910 when they finally gave up the canard. Its a story in which technology, stubbornness and commercialization are intimately mingled; we are concerned here only with the technology.

## 1. Introduction and Historical Background

When the Wrights began their project in 1899, they knew the conventional configuration of an aircraft, invented by Sir George Cayley<sup>[1]</sup> in 1799. Much later, in the same paper reporting successful flights of his rubber-powered model, Alphonse Pénau<sup>[2]</sup> gave an agreement showing how an aft horizontal tail acts to give stability in pitch. Figure 1 shows a replica of his creation, the first successful powered flying machine. However, installation of an aft horizontal tail is neither necessary nor sufficient for an aircraft to possess stability in pitch.

The convincing successes of Cayley and Pénau established the widely adopted view that the key to solving the problem of mechanical flight lay with learning how to construct an intrinsically stable machine. From the beginning of their work, the Wrights followed a different strategy—flight controlled by the pilot.

In August 1899 Wilbur flew a five foot glider to confirm his idea for lateral control by differentially warping the surfaces of a biplane configuration. The kite was also controllable in pitch by changing the angle of attack of the horizontal surface. Simply by shifting the orientation of the control cords, between flights, Wilbur carried out tests with the surface fore or aft of the biplane. He discovered that the kite reacted more sensitively in pitch when the control surface was placed in the canard configuration. That happens because the kite is then unstable, but Wilbur evidently interpreted the behavior in support of his search for more effective control in pitch.

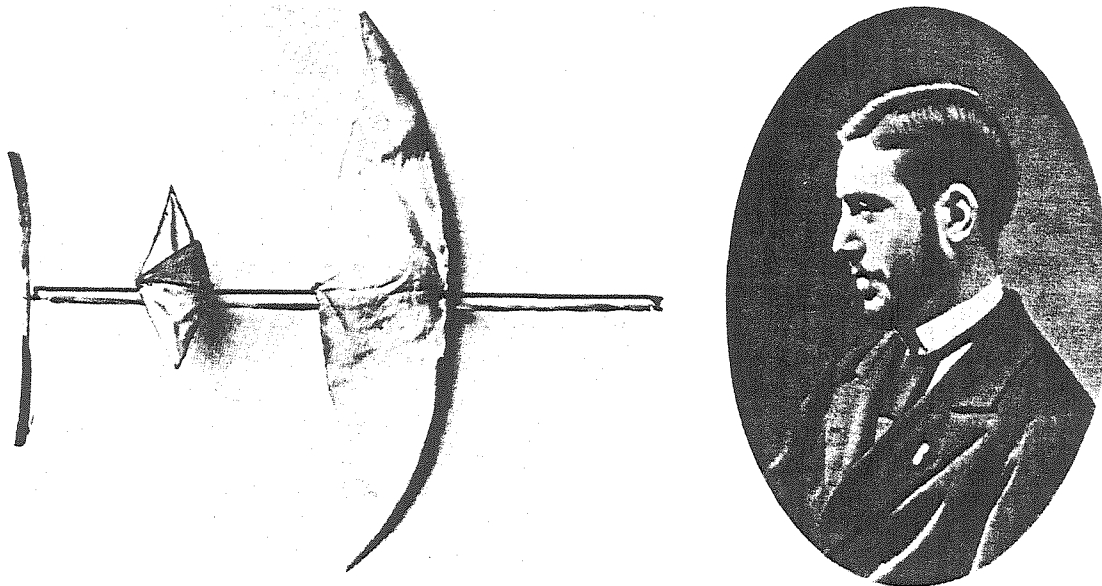


FIGURE 1. Pénaud and his Planaphore, 1871 (Means<sup>[7]</sup>)

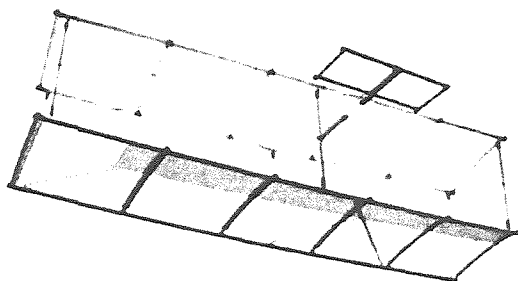


FIGURE 2. Engler's<sup>[3]</sup> replica of Wilbur's 1899 kite.

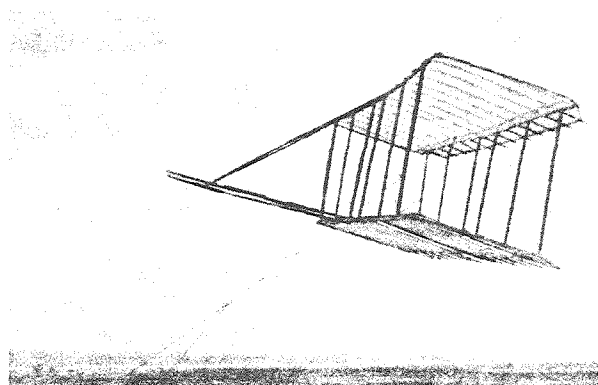


FIGURE 3. The Wrights' 1900 Kite-Glider (Plate 14 of McFarland<sup>[4]</sup>)

The brothers apparently had similar experiences with their kite/glider in 1900. Orville wrote home<sup>[4]</sup> on October 18:

"...We tried it with tail in front, behind, and every other way. When we got through, Will was so mixed up he couldn't even theorize."

Nevertheless, Wilbur soon concluded that both the forward and aft horizontal surfaces would provide acceptable control of his biplane flying machine. At this time, and possibly throughout their program to 1910, the Wrights seem to have assumed that the biplane cell provided all the lift, the horizontal surface

serving only to provide small correcting forces required to “maintain equilibrium”. That idea alone, clearly derivative from their long experience with bicycles, already set the Wrights apart from all their predecessors.

Nevertheless, despite his natural appreciation for the effectiveness of active control by the pilot, Wilbur shared with his predecessors and contemporaries a certain confusion between intrinsic stability as the means for maintaining equilibrium, and the use of control to achieve the same end. In his now-famous letter to Chanute<sup>[5]</sup> he had declared his observation,

“...my observations of the flights of birds convince me that birds use more positive and energetic methods of regaining equilibrium than that of shifting the center of gravity.”

Cayley had invented the use of dihedral, fixing the tips of the wing higher than the root, to maintain lateral equilibrium by providing stability of roll motions. The difference is fundamentally significant: stability of a (possibly) unstable system by active feedback control in contrast to a system intrinsically stable by virtue of its geometry. Despite his supreme commitment to control, Wilbur<sup>[6]</sup> betrayed his confusion about the distinction when he wrote in a letter to Stanley Beach (employed by *Scientific American*) on January 16, 1908,

“In the matter of control, the Farman machine uses nothing but the dihedral angle for lateral control. There seems to be a great diversity of opinion as to the efficacy of this method, but we believe that almost every experimenter who has operated in winds has been compelled to discard it.”

Control of a flying machine was not a new idea. Otto Lilienthal (1848–1896) (Figures 4–6) invented hang-gliding and thereby effectively invented control as well, but in a severely limited form. It was his original idea that following a disturbance in flight, he could restore equilibrium by shifting his weight. Unfortunately, the amount of control available with this method was insufficient to allow Lilienthal to recover from a stall probably caused by a gust on August, 1896. He died a day later due to injuries he suffered in the crash. Percy Pilcher (1866–1899) (Figure 7) also died following a crash in his version of a Lilienthal glider. Although the accident was a result of structural failure, it apparently suggested that control of an aircraft with an aft-horizontal tail might be so restricted as to make the configuration unacceptable.

Thus the immediate history of hang gliding experiences encouraged Wilbur to adopt the canard configuration. Besides—not a minor consideration early in the Wrights’ project—the pilot could see what the control surface was doing, and it offered a very helpful visual indication of the aircraft’s pitch orientation relative to the ground.

So in the first stage of his work, Wilbur became convinced that the canard offered not only successful pitch control but the comfort of visual confirmation. As the Brothers progressed in their development, no reasons appeared to change their basic design—until 1910. The reasons then were imposed externally.

After the Wrights first flew publicly in August and September 1908, the rest of the world understood that successful flight required control about three axes. An enthusiastic community of pioneer designers and aviators had been trying for six years to best the Wrights, with few results. Now with lateral control using wing-warping, their aircraft really did fly! More to the point, moderately skilled pilots could fly them.

Alone among contemporaries, Glenn Curtiss (1878–1930) apparently understood, at least partly, the importance of the Wrights’ innovation. After some practice with gliders and after several unsuccessful

attempts, he and his colleagues in the Aerial Experiment Association (AEA) devised the first practical ailerons, installed in their aircraft the 'June Bug' (Figure 8)

It's an interesting aspect of the AEA design that they initially followed the practice, by then common, of using an aft-horizontal surface, the 'Pénaud tail'. (Figure 8). Only later did they add the canard, probably motivated by the first installation of both surfaces by the French pioneer designer Ferdinand Ferber (1862–1909). (Figures 9 and 10)

Several other designers also used both 'tails', evidently reasoning that the Pénaud tail would provide intrinsic stability, and the Wrights' canard would be used only, or chiefly, for pitch control. Nobody else mimicked Wrights' practice of installing a canard surface only. In none of these episodes did the designers, builders or pilots understand how to assess the effects of geometry and mass distribution on stability.

Thus, after the Wrights' first public flights in August and September 1908, their erstwhile competitors who had lost the race to be first, took from the Brothers *only* the idea and practice of 3-axis control. None were impressed by the canard design which very quickly gained its reputation for unsatisfactory if not outright dangerous, flying qualities. More significantly for the Wrights', their aircraft did not have superior performance.

Still they were not willing to give up their design without a kind of internal battle. First they installed an aft tail on their exciting aircraft, creating a transitional aircraft of which only one existed (Figure 11). No written record of the aircraft's performance and handling qualities exists. Simple estimates given here in Section 5 show, as expected, substantial improvement: the machine was likely statically stable and the pilot must surely have been pleased with the result. Finally in 1910 the Wrights constructed their Model 'B' airplane without the canard, Figure 17.

In all of the Wrights' powered aircraft from 1903 to the Model C, also having only an aft horizontal surface, the biplane cell remained nearly unchanged. Among the seven models, the chord and wingspan differed by about 8% or less from the 1903 *Flyer*. The airfoil sections were not significantly modified because the Wrights had no aerodynamic data to guide them otherwise. They never investigated pitching moments and therefore did not realize the serious problem they had with their thin highly-cambered aircraft (Culick<sup>[10]</sup>). Moreover, more than 90% of the entire mass of all the machines, including pilot, was in the biplane cell. Hence the center of mass could not be moved very far without adding considerable ballast.

The grand result was that the static margin of all the canard designs was negative. Positive stability could be had only by replacing the canard with an aft tail to move the neutral point of the aircraft behind the center of mass. Figure 12, taken from Culick<sup>[10]</sup> shows the interesting progression from 1903 to 1912. The vertical line is located at the leading edges of the six aircraft shown. Figures 18–21 show 3-views of the aircraft, taken from McFarland<sup>[4]</sup>.

Thus the main results of this paper are clear. The analysis and calculations serve only to enumerate details. We have complete geometrical and aerodynamic data only for the 1903 *Flyer*. Reasonable estimates and applications of simple scaling laws allow us to guess quite well the characteristics of the other aircraft, just because the biplane cell was modified so little.

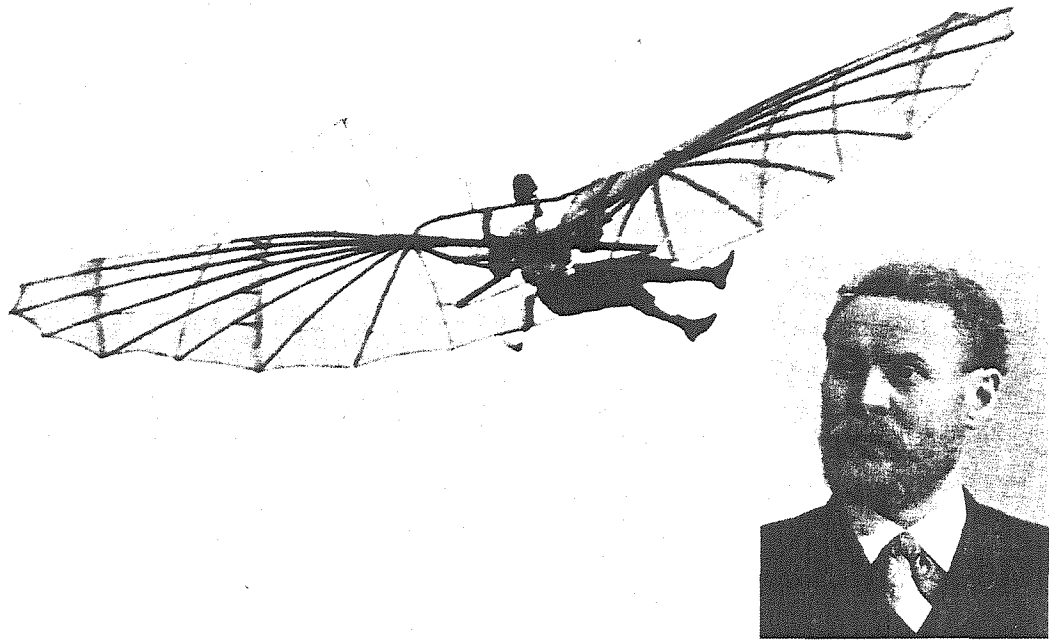


FIGURE 4. Otto Lilienthal and Glider, 1894 (Means<sup>[8]</sup>)

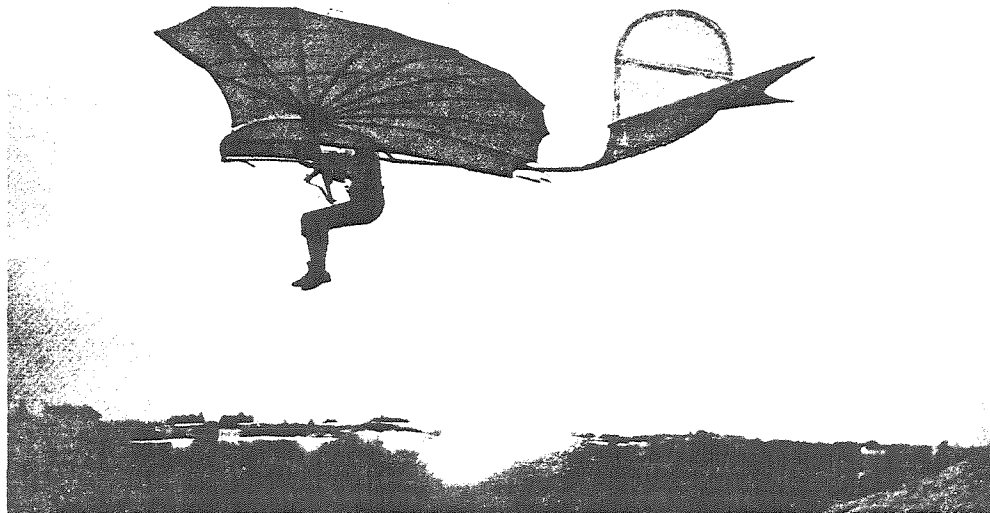


FIGURE 5. Lilienthal's Glider, 16Aug1894 (Heinzerlung and Trischler<sup>[9]</sup>)



FIGURE 6. Lilienthal's Biplane Glider, 1896 (Heinzerlung and Trischler<sup>[9]</sup>)

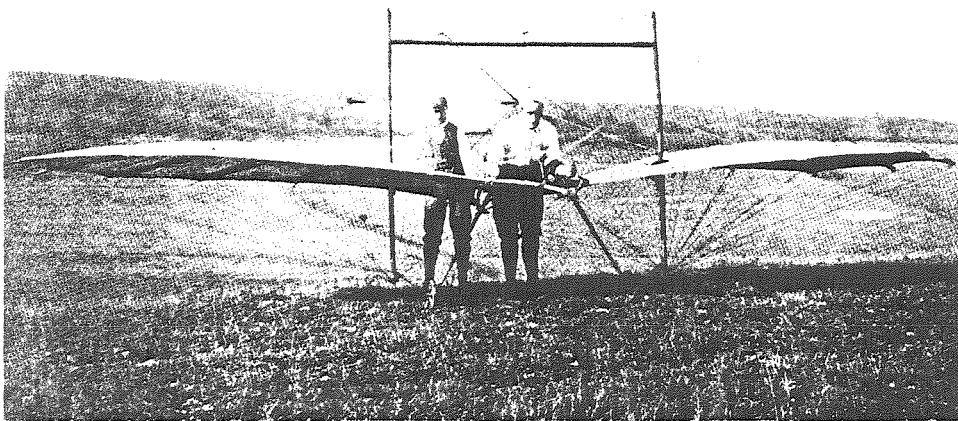


FIGURE 7. Percy Pilcher and *The Hawk*, 1896 (Means<sup>[8]</sup>)

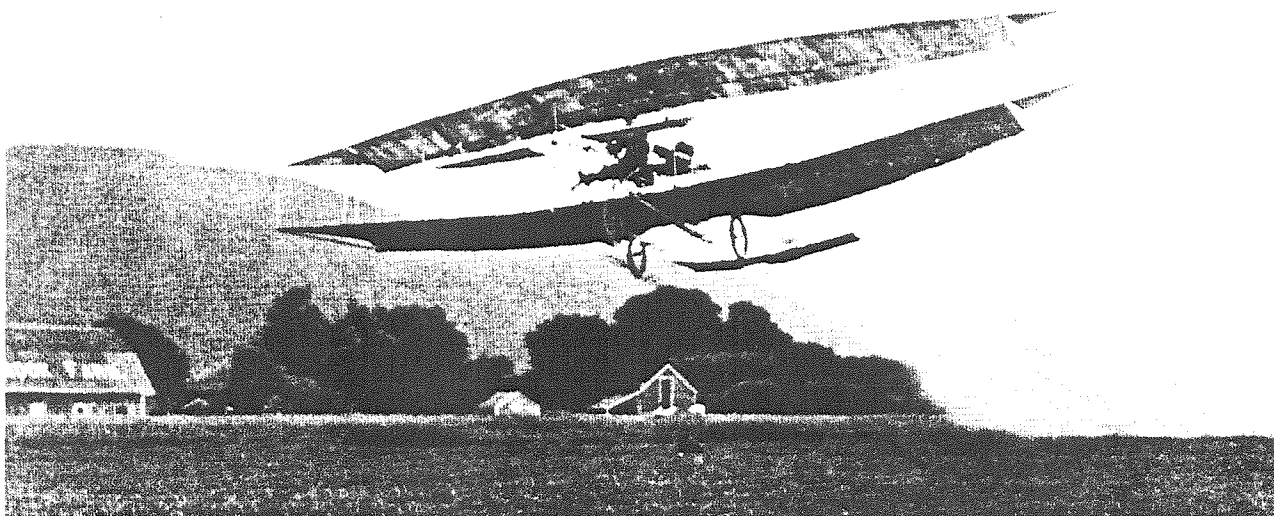


FIGURE 8. The *June Bug* in flight, July 1908. Note the moveable wing tips producing at this moment a roll to the left, evidently executed by the pilot to lift the right wing. Photo by H.M. Benner. (Casey<sup>[10]</sup>)

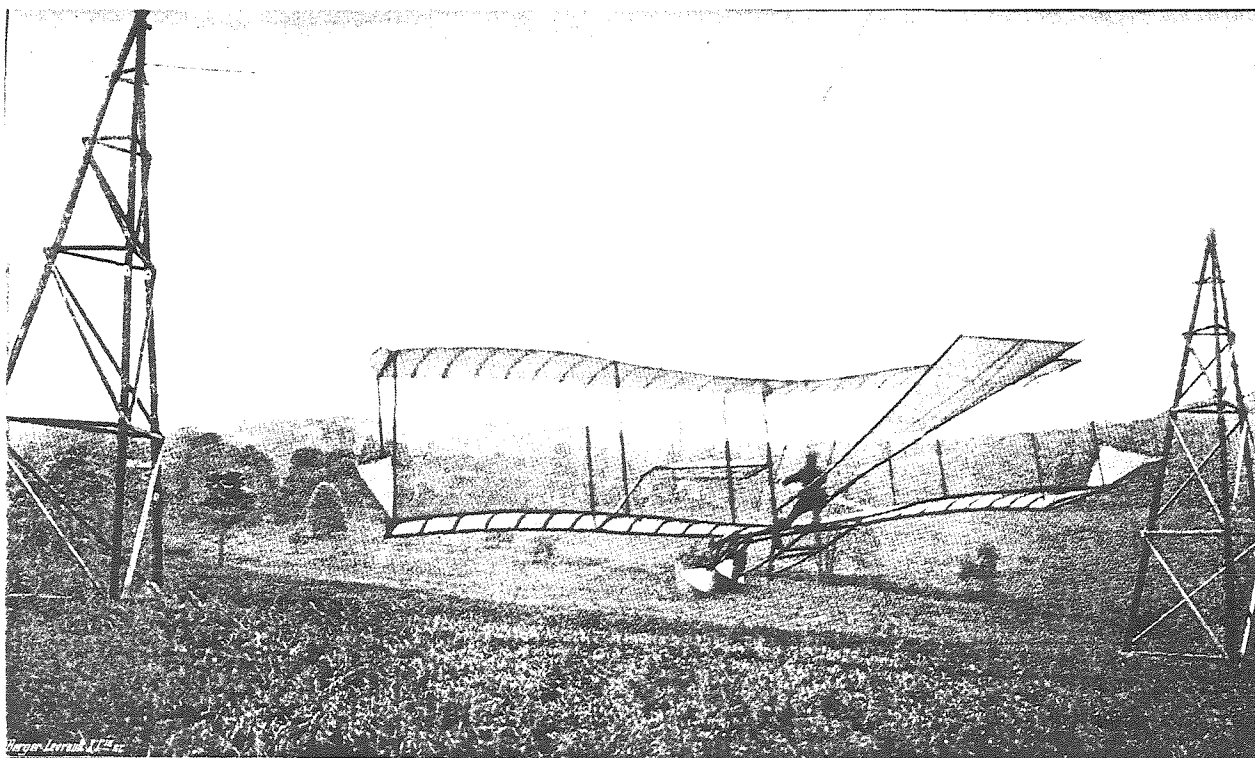


FIGURE 9. Ferber's airplane, 27 May 1905 (Ferber<sup>[11]</sup>)



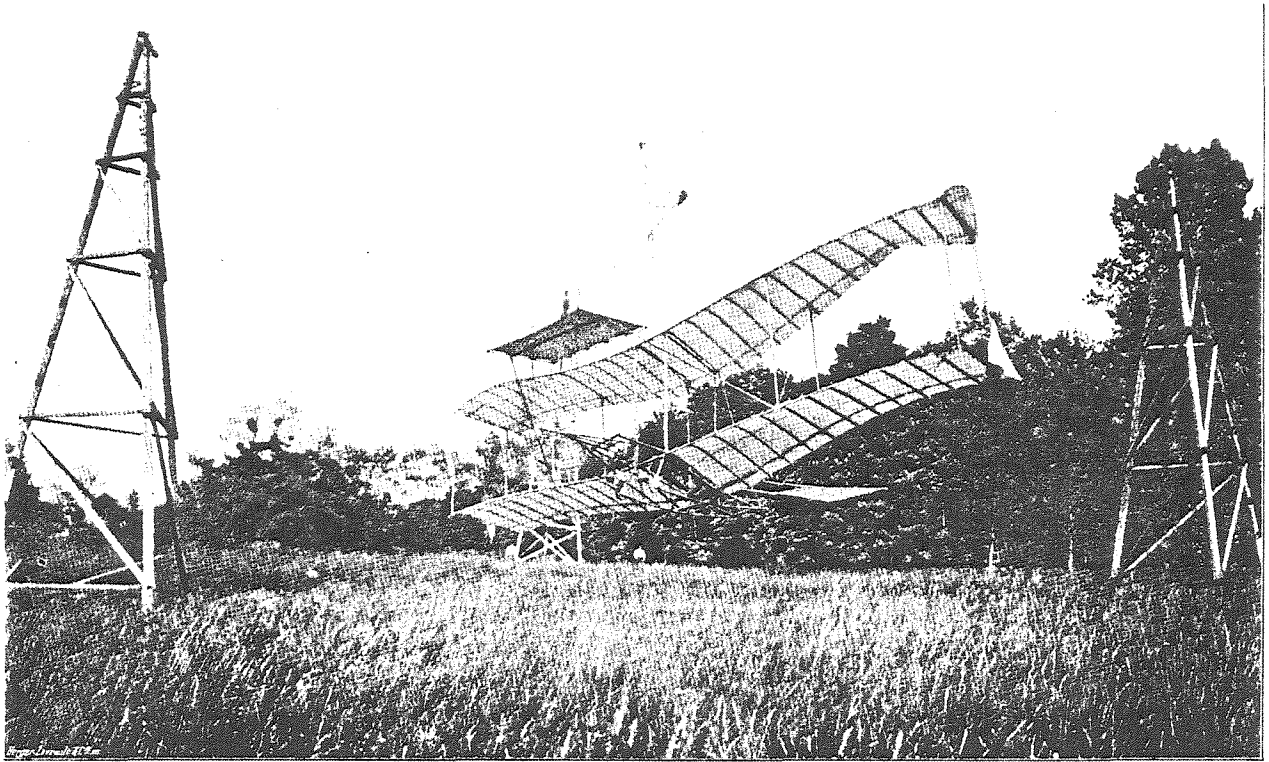


FIGURE 10. Ferber's airplane, June 1905 (Ferber<sup>[11]</sup>)

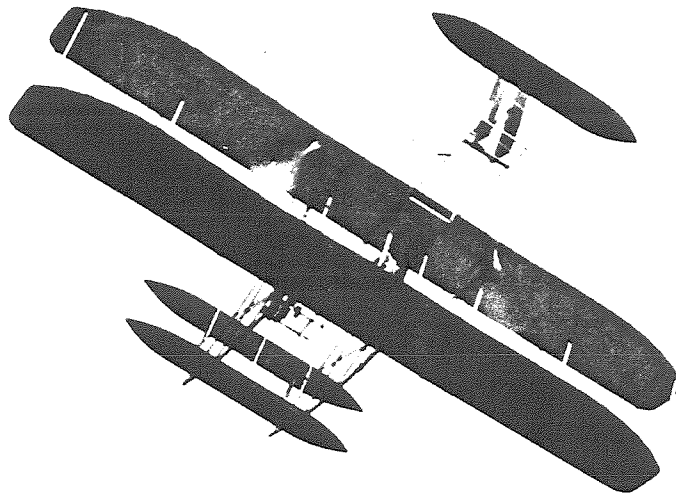


FIGURE 11. Wright *Flyer* with canard and Pénauud tails, 1910 (Ferber<sup>[11]</sup>)

# Wright Aircraft 1903 - 1912

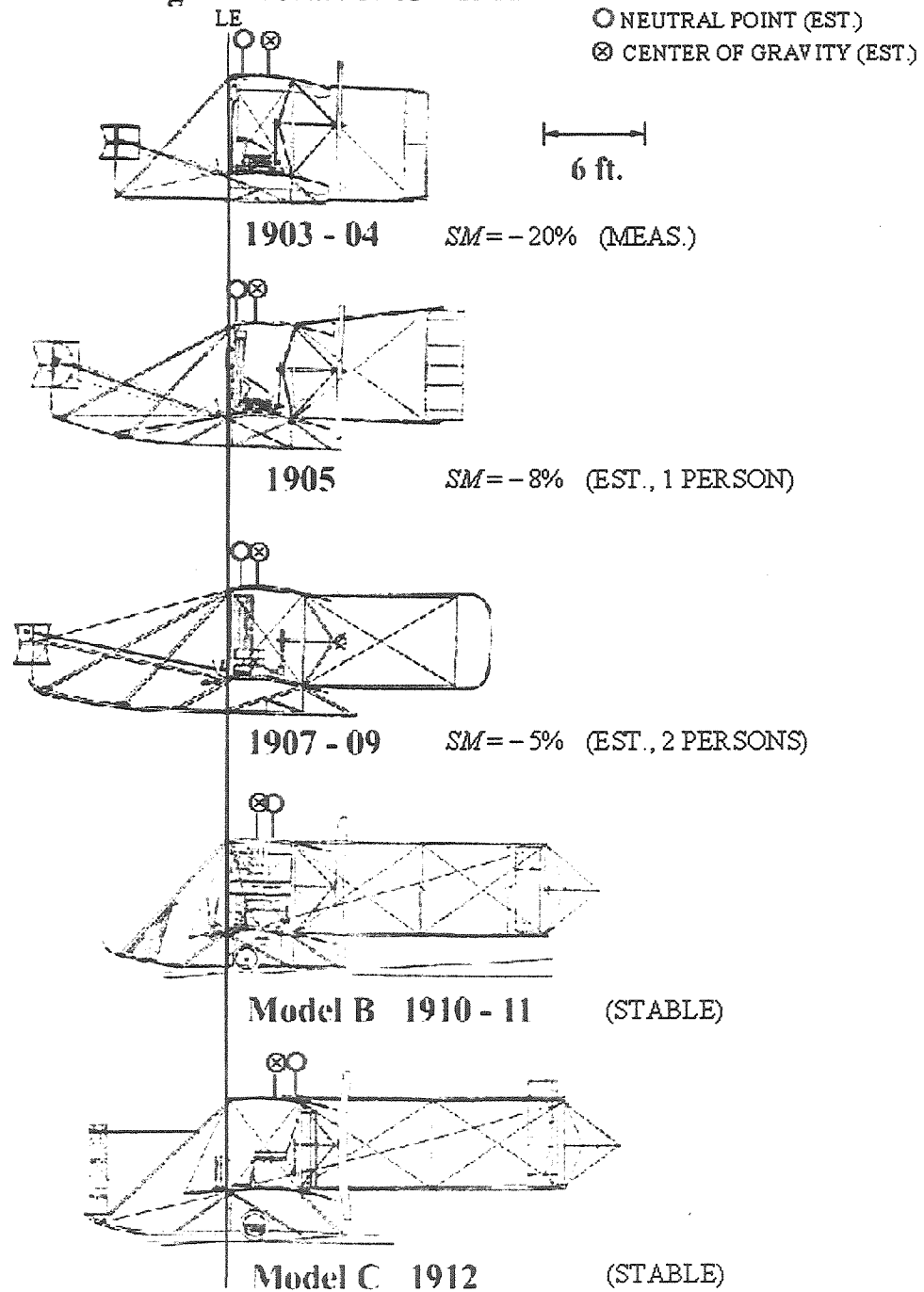


FIGURE 12. Development of the Wright aircraft from the 1903 *Flyer*, a canard, to the conventional configuration of the 1912 Model C

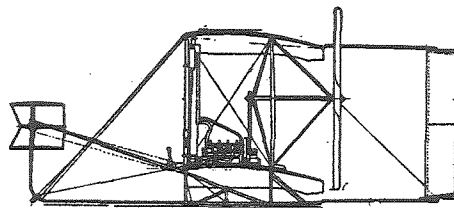
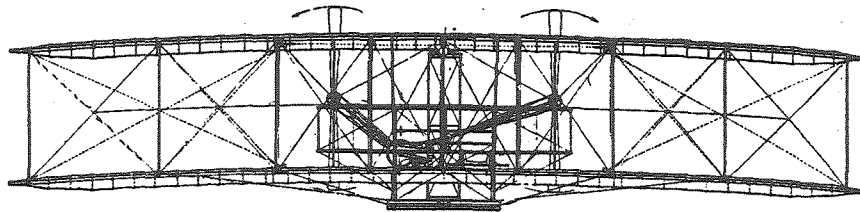
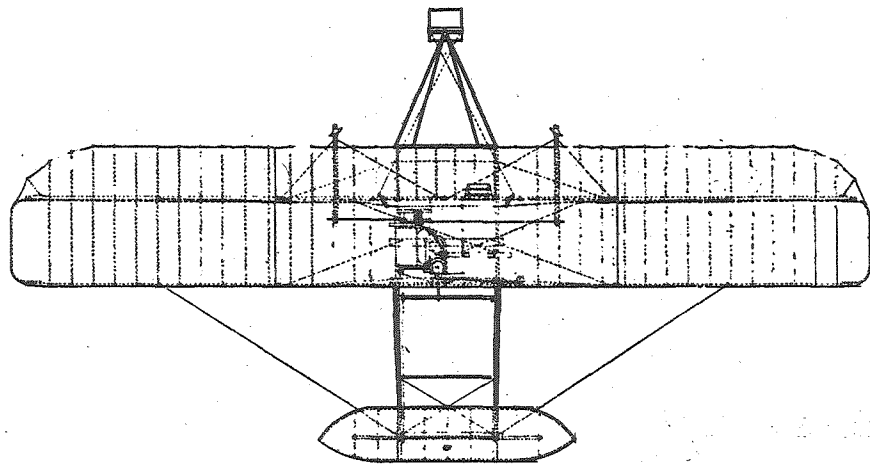


FIGURE 13. 1903 *Flyer*

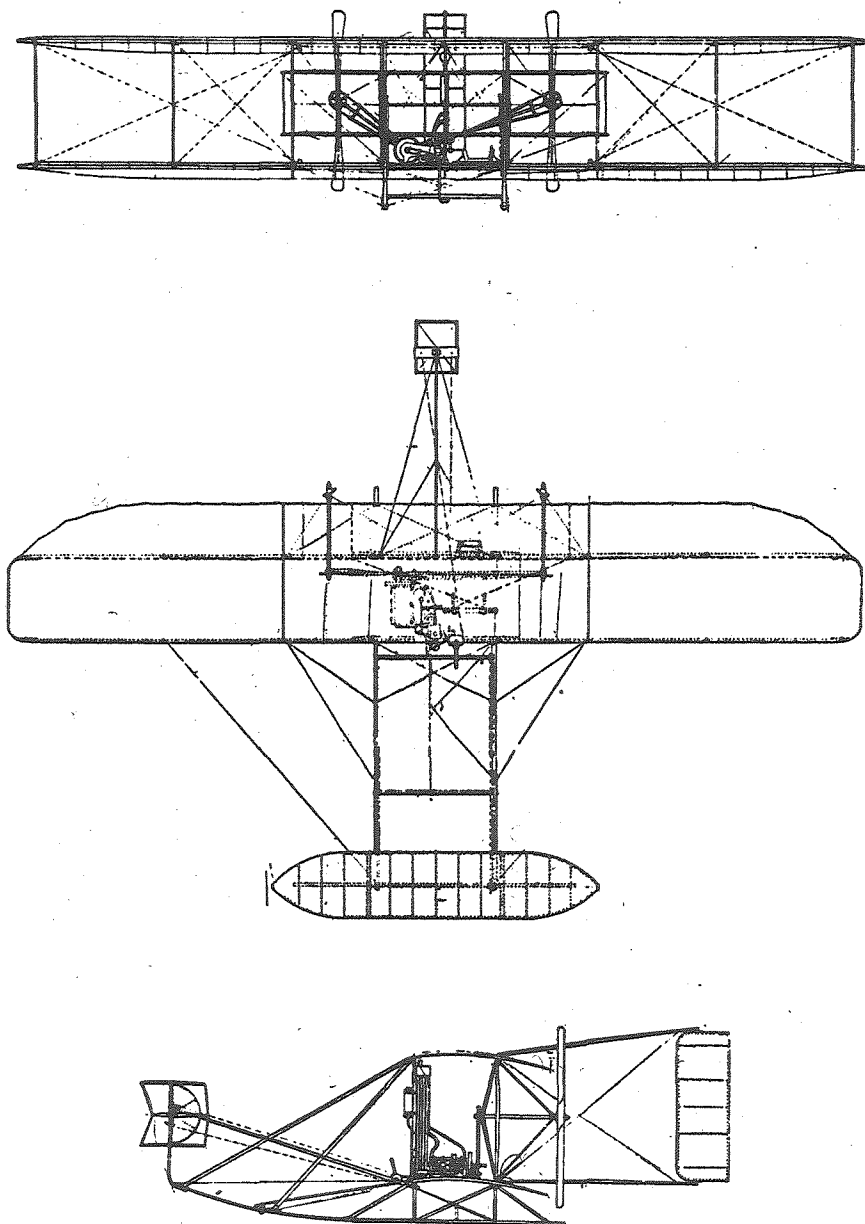


FIGURE 14. 1905 Machine

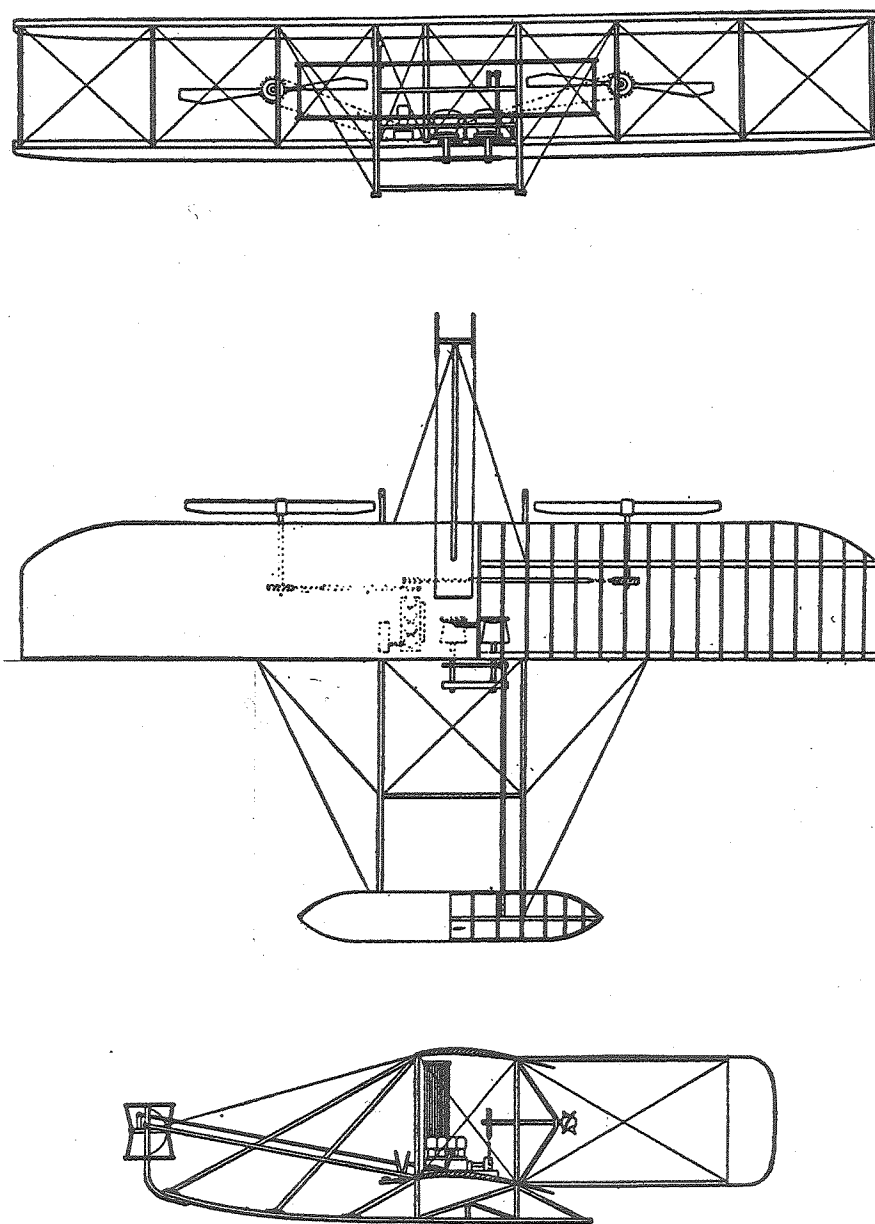


FIGURE 15. 1907-09 Machine

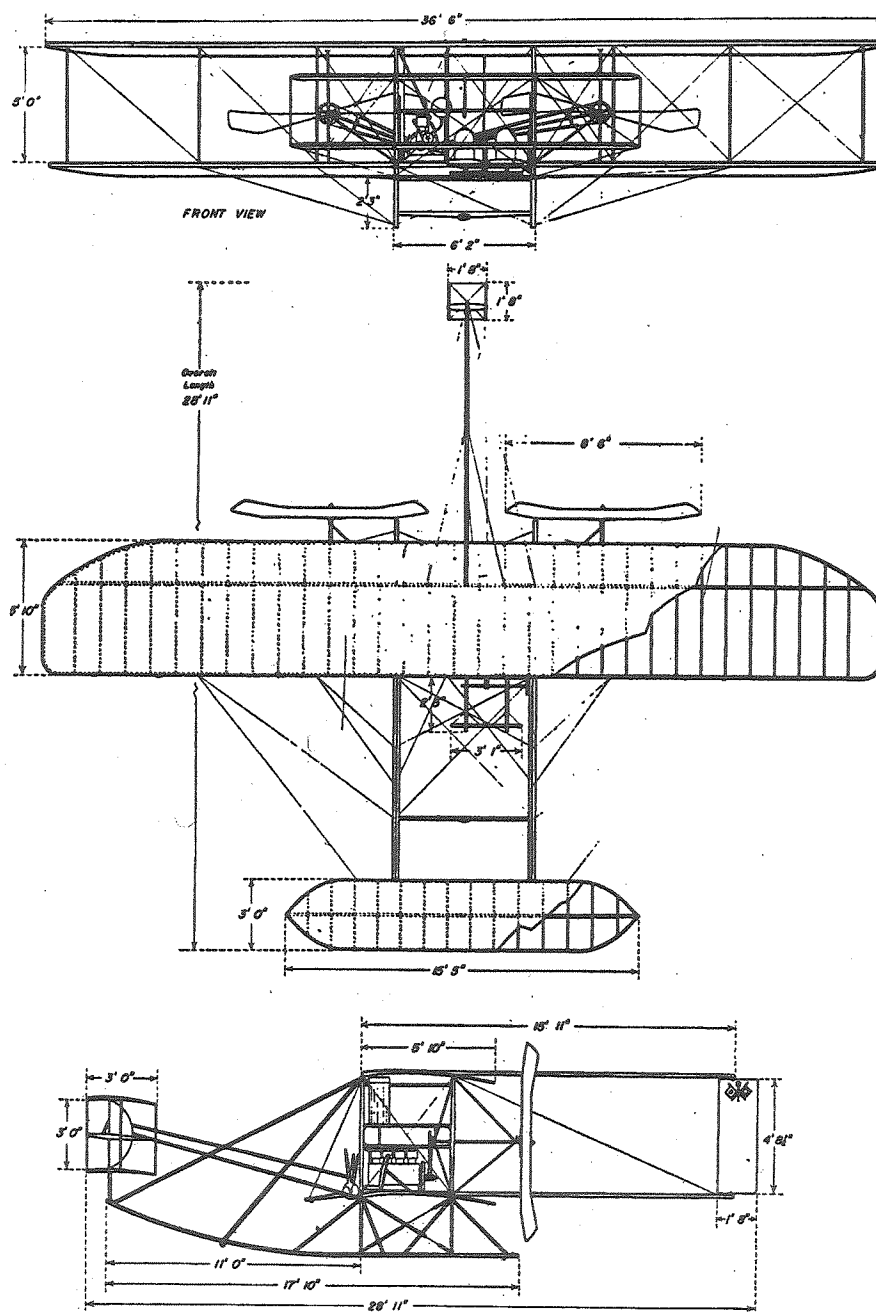


FIGURE 16. 1909 Signal Corps Machine

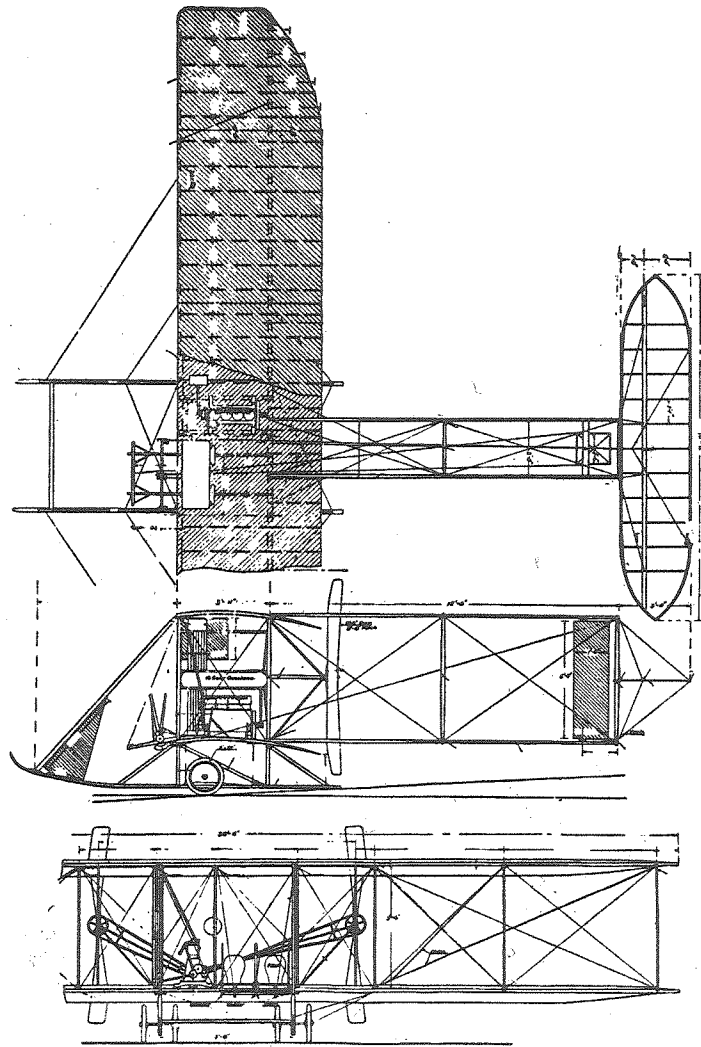


FIGURE 17. Wrights' Model B 1910-1911 (McFarland<sup>[4]</sup>, p. 1198)

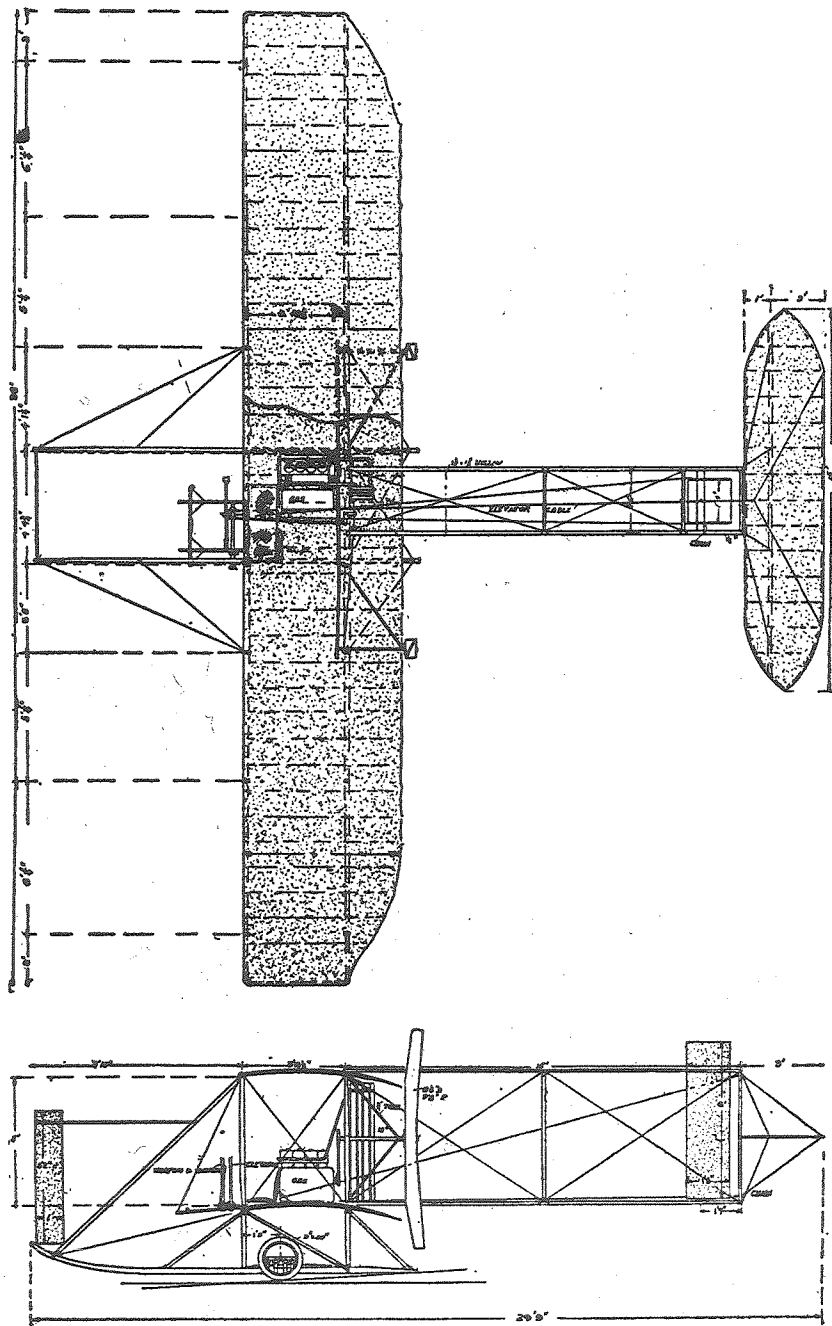


FIGURE 18. 1912 Model C



## 2. Performance of the 1903 *Flyer*

Although the longest flight of the 1903 *Flyer* was only 59 seconds, after a short take-off, estimated to be somewhat greater than fifteen meters, it did reach essentially a cruise condition. The aircraft never flew out of ground effect but contrary to some views, the results we have obtained suggest that it was capable of doing so. Here we include only charts for thrust and power required in steady level cruise flight with no ground effect accounted for.

**2.1. Lift and Drag of the 1903 *Flyer*.** Early in the AIAA Wright *Flyer* Project, two wind tunnel test programs were carried out with 1/6-scale and 1/8-scale models, shown in Figure 19 and 20. The first was constructed of wood, fabric and wire and had warpable surfaces; it had power (a 1/40 HP electric motor) but no data for the effects of power were obtained. The second model made of stainless steel was unpowered; complete static data were obtained in tests carried out at nearly full-scale Reynolds number.

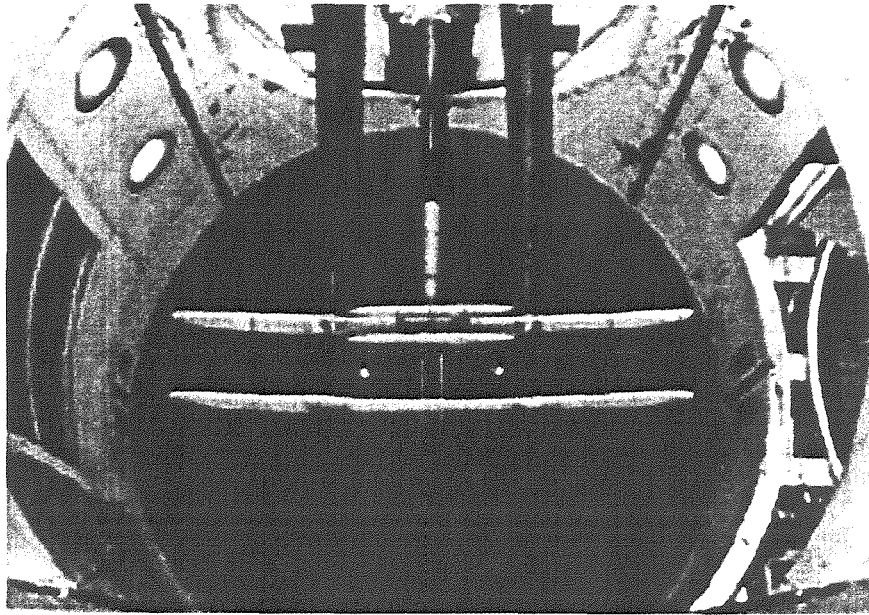


FIGURE 19. 1/6-Scale Model in the GALCIT WInd Tunnel<sup>[19]</sup>

The first major objective of the Project was met in March 1999 with a test program of the full-scale model of the *Flyer* in the Ames tunnel<sup>[24,12]</sup>, Figure 21. Only incomplete and indecisive results were obtained for the effects of power. In general the data obtained from the three sets of tests are in reasonable agreement. Some differences arise because the 1/6-scale model had some unexpected deformations and suffered damage during the tests.

Figure 22 is one example comparing results from the 1/8- and full-scale tests. In our analyses we have used the following approximations to the lift and drag of the *Flyer*

$$C_L = 0.639 + 0.0682\alpha + 0.0579\dot{\alpha} + 0.00567\delta_c \quad (2.1)$$

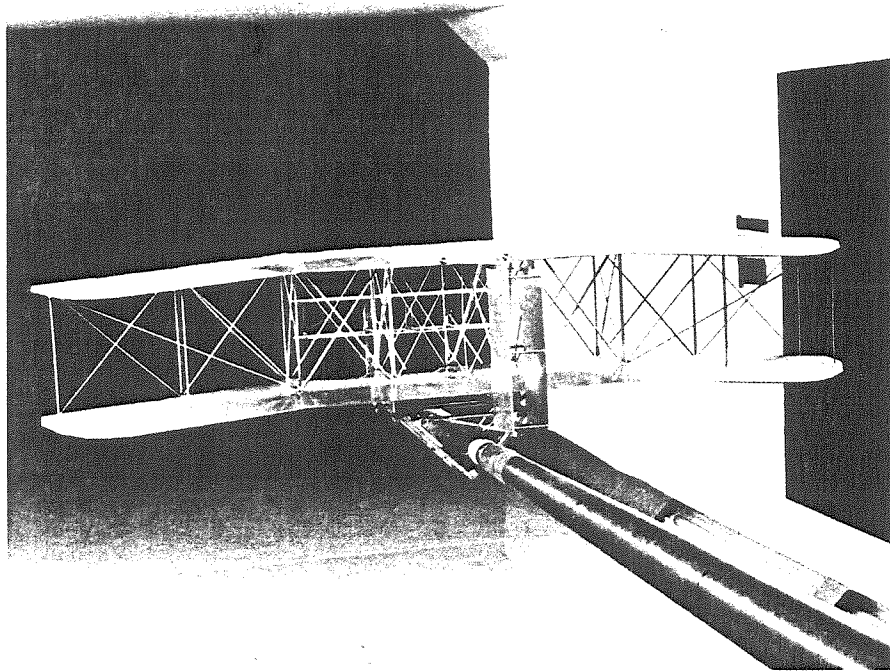


FIGURE 20. 1/8-Scale Model in the Northrop Wind Tunnel<sup>[20]</sup>

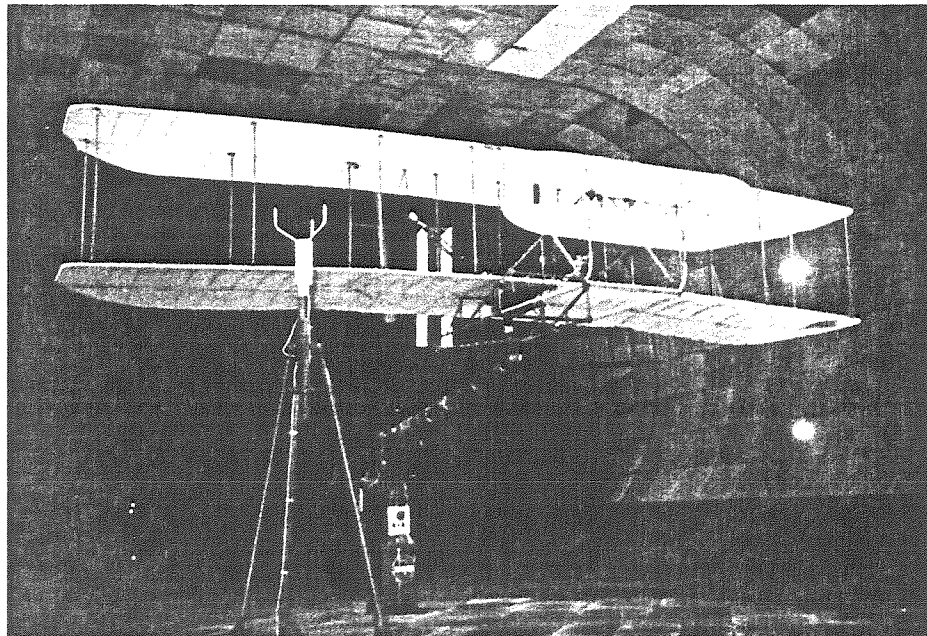


FIGURE 21. The AIAA Full-Scale 1903 *Flyer* in the Ames Wind Tunnel

$$C_0 = 0.079 + 0.1006C_L^2 \quad (2.2)$$

Note that (2.2) gives minimum drag coefficient at zero lift. That is not true for the aircraft, mainly because of the highly cambered thin airfoil. A good approximation to the data shown in Figure 22 is

$$C_D = 0.1231 - 0.1114C_L + 0.1657C_L^2 \quad (2.3)$$

Comparison of numerical results shows that use of (2.2) instead of (2.3) has essentially no effect on the results for thrust and power required, up to three significant figures. Similarly, because (2.2) and (2.3) have practically the same slope of the flight lift coefficient ( $C_L = 0.6$ ) use of (2.2) instead of (2.3) causes no errors in the calculations of linear dynamics.

The formula (2.2) is a good quadratic fit to the data measured with a 1/8-scale steel model and with the AIAA full-scale replica (Jex et al.<sup>[12]</sup>). On the other hand, (2.1) is somewhat more convenient because minimum drag occurs at zero lift. For calculations of performance, the two formulas give indistinguishable results. Moreover, at realistic values of the lift coefficient ( $C_L \sim 0.6$ ), the two curves have nearly identical slopes and thus the linearized forms give essentially the same results for linear dynamical behavior. We use only (2.1) in the remainder of this paper.

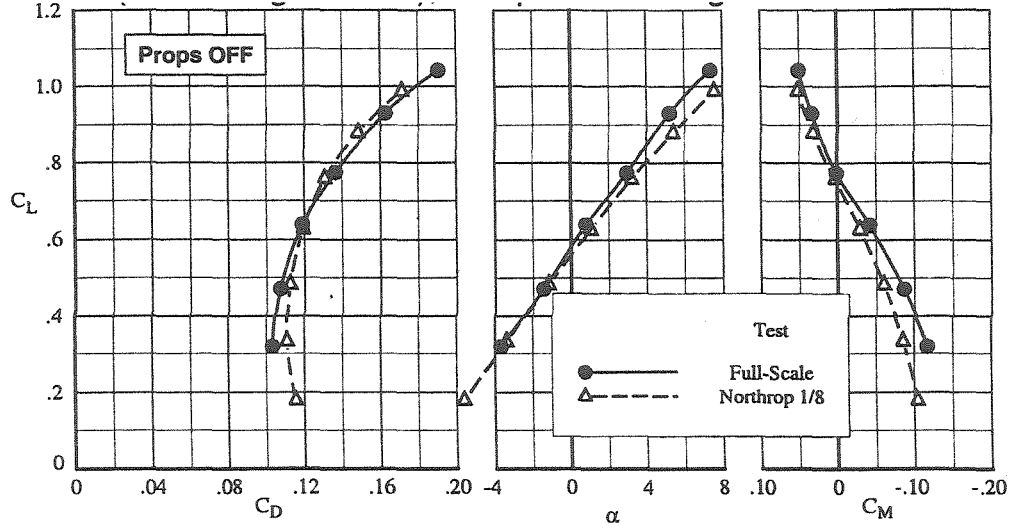


FIGURE 22. Wind Tunnel Data – Comparisons of 1/8-Scale and Full-Scale Data

As an independent effort in the project, in 1981, C. McPhail prepared a thorough report of many characteristics of the 1903 airplane. In particular, his theoretical estimate of the zero lift drag coefficient (0.0855) agrees very well with the value of 0.0815 measured by Bettes and Culick<sup>[19]</sup> but is about 7% higher than the value implied by the data in Figure 22.

Because the aircraft is a complicated collection of many varied parts, and particularly due to the thin cambered airfoil, the drag coefficient is not minimum at zero angle of attack. We use the approximation having minimum at zero lift coefficient,

We approximate the lift coefficient with the formula

$$C_L = C_{L_0} + C_{L_\alpha} \alpha + C_{L_{\dot{\alpha}}} \dot{\alpha} + C_{L_{\delta_c}} \delta_c \quad (2.4)$$

The coefficients  $C_{L_0}$ ,  $C_{L_\alpha}$  and  $C_{L_{\delta_c}}$  are estimated from wind tunnel data but  $C_{L_{\dot{\alpha}}}$  must be estimated to give the explicit result used in our calculations:

**2.2. Thrust and Power Required for the 1903 *Flyer*.** As part of the effort by the AIAA Los Angeles Section's project to build a flyable replica of the 1903 *Flyer* estimates of performance are essential to establishing the requirements for the propulsion system. Elementary calculations based on the lift curve and drag polar are entirely adequate. Beginning with the original work by Millikan<sup>[13]</sup> and developed to its final form by Oswald<sup>[14]</sup> and Rockefeller<sup>[15]</sup> the method has been explained in several texts, e.g., Perkins and Hage<sup>[16]</sup>, Etkin<sup>[17]</sup> and Shevell<sup>[18]</sup>. The main results are the formula for the thrust and power required, in steady level flight

$$T_R = D_m \left[ \left( \frac{V}{V_m} \right)^2 + \left( \frac{V_m}{V} \right)^2 \right] \quad (2.5)$$

$$P_R = K_1 V + K_2 \frac{1}{V} \quad (2.6)$$

where

$$\begin{aligned} V_m &= \left( \frac{K_2}{K_1} \right)^{1/4} \\ D_m &= 2\sqrt{K_1 K_2} \\ K_1 &= \frac{1}{2} \rho S C_{D_p} \\ K_2 &= 0.1006 \frac{2W^2}{\rho S} \end{aligned} \quad (2.6)_{a,b,c}$$

and  $D_m$ ,  $V_m$  are the values of the drag and velocity at the angle of attack (i.e., lift coefficient) for minimum thrust required.

Figures 23 and 24 show the thrust and power required for the 1903 *Flyer* at its original weight with pilot (750 pounds) for several altitudes.

Note that the stall speed is about 40 ft/s or 25 mph and the minimum power required is roughly eight horsepower. The corresponding thrust required is 135–140 pounds. Generally accepted values for the power output of the Wrights' engine are 14–15 horsepower when cold and about 12 horsepower when hot. To produce the minimum power required for flight with 12 HP, the propellers and chain drive transmission system must have best efficiency  $8/12 = 66\%$  at 25 mph. Measurements reported by Ash et al.<sup>[23]</sup> suggest that in fact the efficiency was much higher, more than 80% at the same values of  $J = V/ND$ .

That result seems somewhat high, a result that has prompted recent computations (Ash et al.)<sup>[23]</sup>. The predicted values are surprisingly close to those measured, but the computations seem not to account for three-dimensional effects in the flow field. Thus, if we assume that the values of drag are accurate, we should tentatively conclude that the engine probably generated more than 12 horsepower when hot.

This matter is important to recreating a *Flyer* to be flown safely and reliably. Therefore, as part of the AIAA's effort, computations of the propeller characteristics are being carried out with three-dimensional effects accounted for.

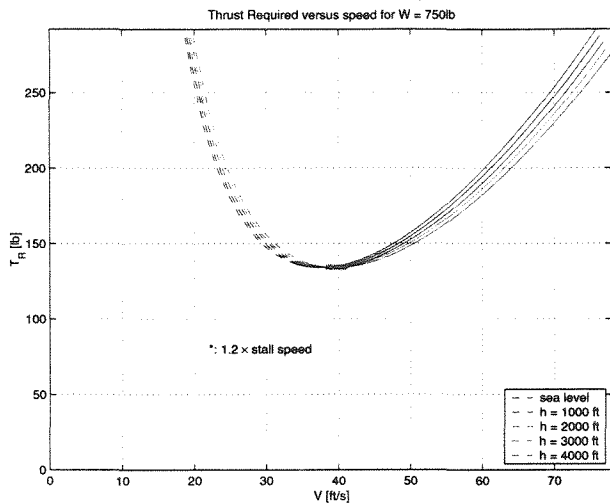


FIGURE 23. Thrust Required versus speed for  $W = 750\text{lb}$

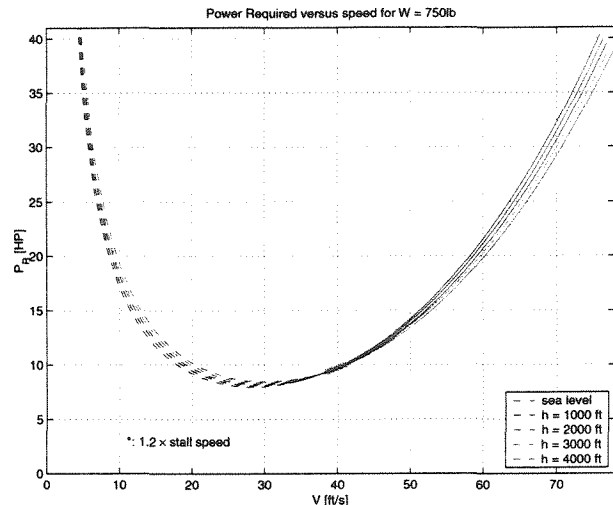


FIGURE 24. Power Required versus speed for  $W = 750\text{lb}$

**2.3. Estimated Take-Off Distance.** The original *Flyer* flew from a sixty-foot long take-off rail and lifted-off in about forty-five feet. However, the four flights on December 17, 1903 were made in a wind estimated to have average speed 25 mph. That is a reported value we assume here, giving a very comfortable ground speed of about<sup>1</sup> 5–7 mph. Without the strong wind—now regarded as an unsafe condition for flight with an aircraft possessing stall speed about 28–30 mph—the Wrights could not have made successful take-offs from their short rail. The aircraft with the original engine and propellers is underpowered.

Take-off performance for a particular flight is difficult to estimate accurately owing to the many uncertainties, including notably the pilot's technique. We have carried out a calculation based in the analysis given by Perkins and Hage<sup>[16]</sup>. For the lift and drag curves discussed above, we have concluded that the take-off distance in still air must be at least 120 feet. Ground effect reduces the minimum thrust required by about 12–14%, reducing the take-off distance by 8–10%. In any case, the take-off distance in still air certainly exceeds sixty feet by a large amount.

Thus we conclude that the 1903 *Flyer* was seriously underpowered, a conclusion implying that attempting to fly an unmodified replica from a sixty-foot rail is an unsafe venture. Success is obviously possible as the Wrights showed, to their everlasting honor. However, the risks are considerable if the original propulsion system is replicated with intentions to mimic accurately the historic take-offs and flights as well. On the other hand, failure or partial success might be regarded as further recognition of the Wrights' remarkable achievement.

### 3. Longitudinal Static Stability of the 1903 *Flyer*

Much has been written about the pitch instability of the 1903 *Flyer*. Even after the Wrights had improved their canard design, the instability remained, although lessened. All who were acquainted with the aircraft

<sup>1</sup>We have made no attempt to settle in precise most likely values of wind, or of the aircraft's actual airspeed and power available. It seems impossible to do so with credible accuracy, due to the absence of accurate information. In this paper we are interested mainly in estimating the conditions under which the Wrights flew.

were at least aware of its difficult flying qualities. Hooven<sup>[29]</sup> was first to make quantitative estimates of stability based on the modern ideas of aircraft dynamics. However the necessary aerodynamic data were not available until the two sub-scale test programs conducted as part of the AIAA Wright *Flyer* Project (Bettes and Culick<sup>[19]</sup>; Heglund et al.<sup>[20]</sup>). Subsequently, Hooven<sup>[30]</sup> wrote the first computer simulation program for motions in the plane of symmetry only; and Culick and Jex<sup>[21]</sup> and Jex and Culick<sup>[22]</sup> reported the first detailed analysis of the controls-fixed and piloted motions of the aircraft.

Calculation of static stability follows conventional practice covered thoroughly by Etkin<sup>[17]</sup> and used in the works cited above. Only the notation and some of the definitions differ in minor details. The biplane wing and canard are approximated as single surfaces sketched in profile in Figure 25. For aerodynamic characteristics we use our best estimates based on the sub-scale tests and on the full-scale test program carried out at the NASA Ames Research Center (Cherne, Culick and Zell<sup>[24]</sup>; Jex et al.<sup>[12]</sup>).

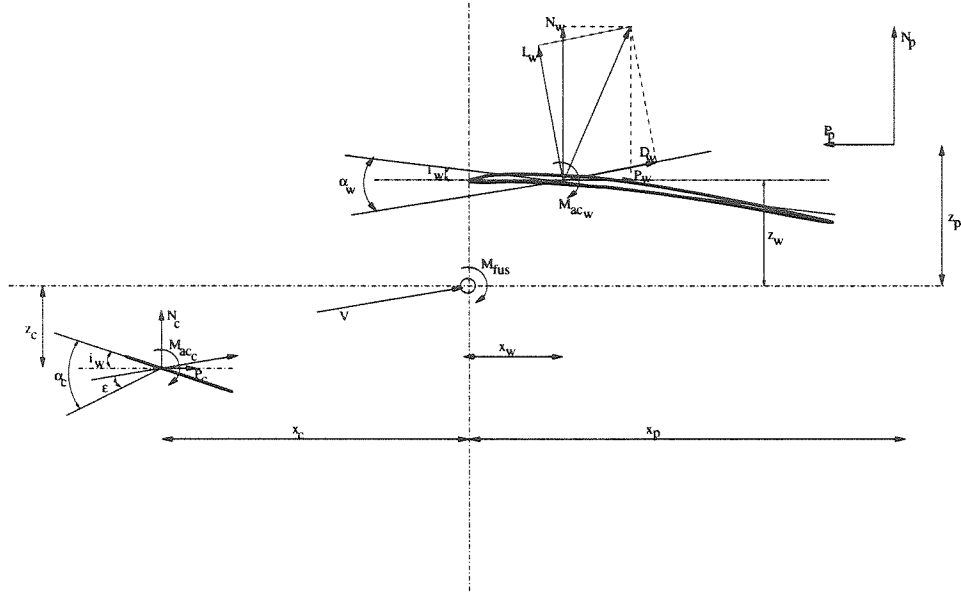


FIGURE 25. Simplified longitudinal forces and pitching moments acting on the 1903 *Flyer*

Analysis based in Figure 26 leads to the formulas for the coefficients of forces in directions normal,  $(\ )_n$  and parallel,  $(\ )_p$  to the skid line:

$$\begin{aligned} C_{n_w} &= C_{L_w} + C_{D_w}(\alpha_w - i_w) = C_{L_w} + (C_{D_{0_w}} + KC_{L_w}^2)(\alpha_w - i_w) \\ C_{p_w} &= -C_{L_w}(\alpha_w - i_w) + C_{D_w} = C_{D_{0_w}} + KC_{L_w}^2 - C_{L_w}(\alpha_w - i_w) = C_{D_{0_w}} + KC_{L_w}^2 - C_{L_w}(\alpha_w - i_w) \end{aligned} \quad (3.1)a,b$$

Similarly, the coefficients of pitching moment about the axis through the origin located at distance  $z_w$  below the leading edge of the equivalent single wing is

$$\begin{aligned} C_m &= \left( -C_{D_{0_w}} i_w + (C_{D_{0_w}} + C_{L_{\alpha_w}}) \alpha_w - C_{L_{\alpha_w}} \alpha_{0L_w} + K(\alpha_w - i_w) C_{L_{\alpha_w}}^2 (\alpha_w - \alpha_{0L_w})^2 \right) \frac{x_w}{c_w} + \\ &+ \left( C_{D_{0_w}} + KC_{L_{\alpha_w}}^2 (\alpha_w - \alpha_{0L_w})^2 - C_{L_{\alpha_w}} (\alpha_w - i_w) (\alpha_w - \alpha_{0L_w}) \right) \frac{z_w}{c_w} + C_{m_{ac_w}} + C_{m_{fus}} \\ &+ (C_{L_{\alpha_c}} (\alpha_w + i_w + \epsilon + \alpha_{0L_c} + i_c)) \frac{S_c}{S_w} \frac{q_c}{q_w} \frac{x_c}{c_w} \end{aligned} \quad (3.2)$$

With this result, the slope of the moment curve, defining static stability, is

$$\begin{aligned}
C_{m_\alpha} = & - \left( C_{D_{0w}} + C_{L_{\alpha_w}} + K C_{L_{\alpha_w}}^2 (\alpha_w - \alpha_{0L_w})^2 + 2K(\alpha_w - i_w) C_{L_{\alpha_w}}^2 (\alpha_w - \alpha_{0L_w}) \right) \frac{x_w}{c_w} + \\
& + \left( 2 \left( K - \frac{1}{C_{L_{\alpha_w}}} \right) C_{L_{\alpha_w}}^2 (\alpha_w - \alpha_{0L_w}) - C_{L_{\alpha_w}} (\alpha_{0L_w} - i_w) \right) \frac{z_w}{c_w} \\
& + C_{L_{\alpha_c}} \left( 1 + \frac{d\epsilon}{d\alpha} \right) \frac{S_c}{S_w} \frac{q_c}{q_w} \frac{x_c}{c_w}
\end{aligned} \tag{3.3}$$

Both static and dynamic stability are assessed for steady level flight, defined by the three equations

$$\begin{aligned}
\text{Lift} &= \text{Weight} \\
\text{Thrust} &= \text{Drag} \\
\text{Pitching Moment} &= 0
\end{aligned} \tag{3.4} \text{a, b, c}$$

We assume that the propulsion system is adjusted so the second equation is satisfied. In dimensionless form the first equation becomes a formula for the lift coefficient:

$$C_L = \frac{W}{q_\infty S_w} \tag{3.5}$$

where  $q_\infty = \frac{1}{2} \rho V^2$  is the dynamic pressure. There are two unknown quantities at this point,  $C_L$  (or the angle of attack,  $\alpha$ ) and the speed  $V$ . We assume, of course that the atmospheric conditions are given so  $\rho$  is known.

Application of the trim condition (3.4)c, serves two purposes; it gives the required value of the lift coefficient in the canard (if  $\bar{q}$  is known) and formally is a second relation between the angle of attack of the aircraft and the flight speed (i.e.,  $q_\infty$ ).

Static stability is then determined by computing the slope (3.3) of the moment curve. Well-known reasoning<sup>[17,18]</sup> leads to the conclusion that  $C_{m_\alpha}$  must be negative for static stability. The statement  $C_{m_\alpha} = 0$ , the condition for neutral stability, gives a formula for the only remaining parameter,  $x_{CG}$ , the position of the center of mass, the origin for the axis of pitching moments. The value of  $x_{CG}$  when  $C_{m_\alpha} = 0$  is called the “neutral point”. Thus, if the center of mass lies at the neutral point, the aircraft is neutrally stable. Further calculations that may be found in the references cited, lead to the important fundamental conclusion that the aircraft is stable if its actual center of mass lies forward of the neutral point. Expressed in units of chord, the difference  $x_{CG} - x_{np}$  is called the static margin, SM:

$$SM = \frac{x_{CG}}{c} - \frac{x_{np}}{c} \tag{3.6}$$

Substituting the known characteristics of the 1903 *Flyer* gives a predicted static margin of  $-25.8\%$ . See Table 1 in Section 5 for a listing of the characteristics used here.

#### 4. Dynamics of the 1903 *Flyer*

Many years ago Culick and Jex<sup>[21]</sup> and Jex and Culick gave comprehensive discussions of the dynamics of the 1903 *Flyer*. The only change from then to now is the recent acquisition<sup>[12]</sup> of aerodynamic data for a full-scale replica of the aircraft, essentially confirming the truth of the sub-scale (1/6 and 1/8) available for the earlier works.

For analyzing the dynamics, we use the conventional linear equations for rigid aircraft (see, for example, the texts cited earlier, but particularly the well-known monograph by McRues, Ashkenas and Graham<sup>[25]</sup>).

**4.1. Longitudinal Dynamics.** Because the 1903 *Flyer* is statically unstable in pitch, its longitudinal (pitching) motions are dynamically unstable as well. Its open loop response, with no control by a pilot, diverges. Figure 26 shows an example of the response to a triangular input to the canard deflection. The doubling time is roughly 0.5s, presenting a serious challenge to a pilot.

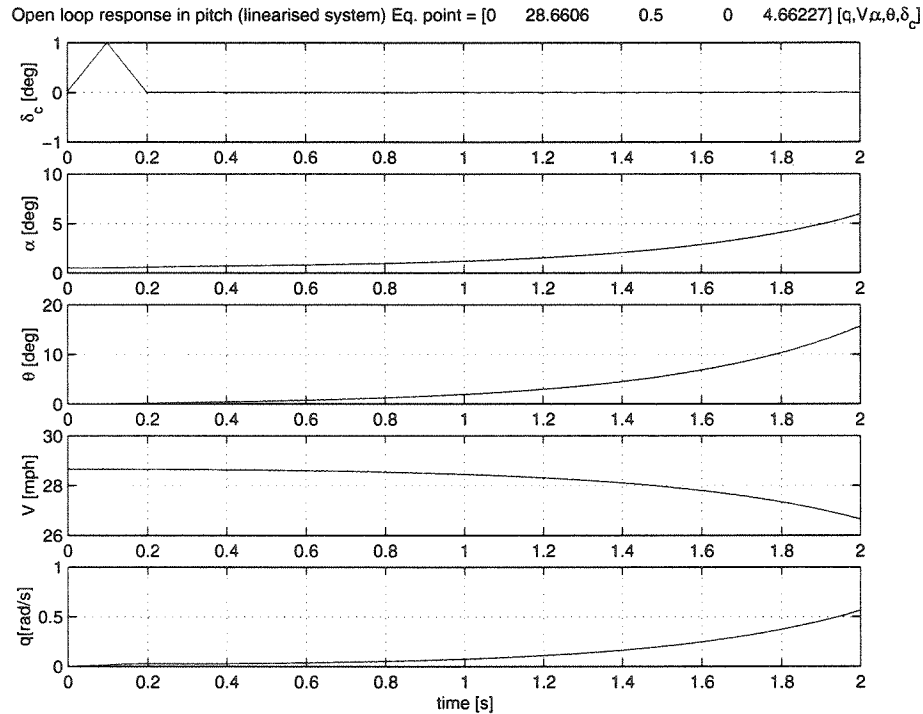


FIGURE 26. Open Loop Response of the 1903 *Flyer* to a Triangular Disturbance of the Canard Setting. (a) Pitch Attitude Angle; (b) Angle of Canard Deflection.

The aircraft can be controlled by a sufficiently attentive pilot. A root locus plot is shown in Figure 27 based on pilot control proportional to the error in pitch angle, i.e. pure proportional control. With a gain of somewhat less than two (i.e. two degrees of canard correction for one degree of observed error), the unstable root at  $25^{-1}$  has been driven into the left half plane and the dominant motion is a lightly damped oscillation. Figure 28 shows the closed-looped response to a step command input of pitch angle,

Interpretation of this behavior is somewhat more complicated than the familiar description of longitudinal motions in terms of the phugoid and short period modes. See Etkin<sup>[17]</sup> and Culick<sup>[26]</sup> for explanations. However the root locus shows clearly that the pilot can control the aircraft in pitch, the dominant motion being an oscillation not heavily damped and having frequency in the range where pilot-involved oscillations (PIO) are a genuine possibility (the period is about one second). The response during an altitude change from level flight to a small angle of climb, Figure 28, confirms this conclusion.



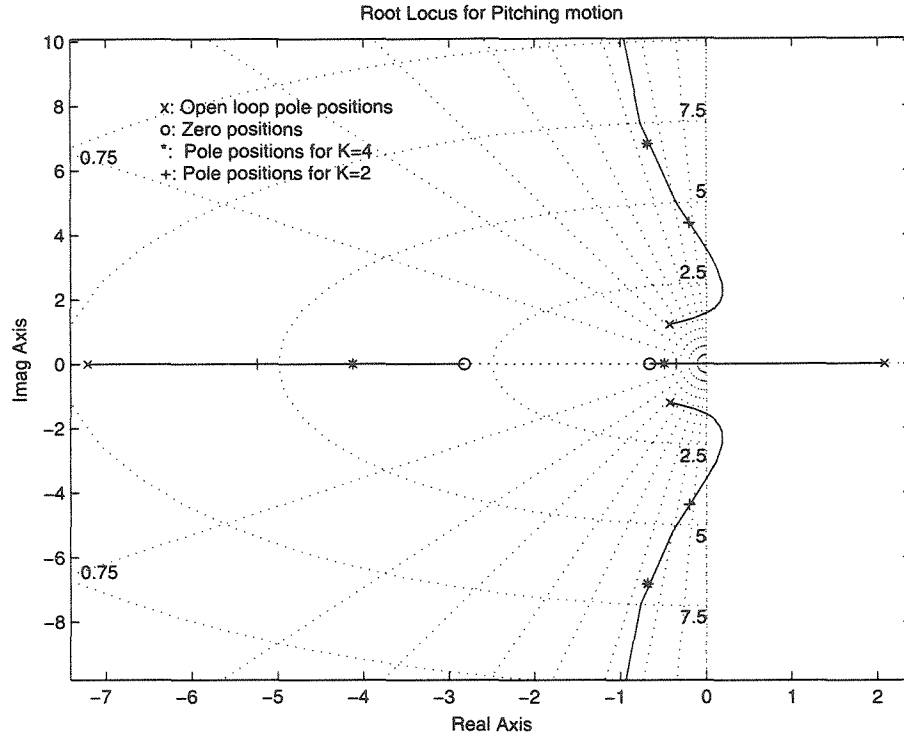


FIGURE 27. Locus of dynamic roots for longitudinal motion of the 1903 Wright *Flyer*; proportional pilot control.

**4.2. Lateral Dynamics.** The lateral dynamics of the 1903 *Flyer* are strange, and troublesome for the pilot, because the negative dihedral trussed into the wings causes the aircraft to be unstable in roll. Because the directional stability is small, the natural stick-fixed modes are a divergence growing out of an unstable spiral mode, and a slightly damped lateral or Dutch roll oscillation having period around one second. Figure 29 shows the open loop time response to a square pulse change of wing warp. The doubling time of the divergence is about two seconds.

The root locus in Figure 30 confirms that a reasonably skilled pilot can control and stabilize the lateral motions. We assume here that the warp and rudder controls are linked, as in the original aircraft, corresponding to a particular use of the rudder by the pilot if the controls are not linked.

Figure 31 illustrates the time response of the piloted aircraft following a triangular input to the warp angle. The aircraft responds sluggishly but eventually settles down to a steady turn having constant bank angle.

These results, not very different from those reported many years ago<sup>[21,22]</sup> serve mainly to confirm what the Wrights demonstrated in 1903, that their aircraft was indeed controllable. So what have we learned? Mainly, we have been able to quantify the flying and handling qualities of the airplane. With the aerodynamic and inertial data, we have the firm basis for constructing a simulator faithfully representing flight of the first successful powered aircraft.

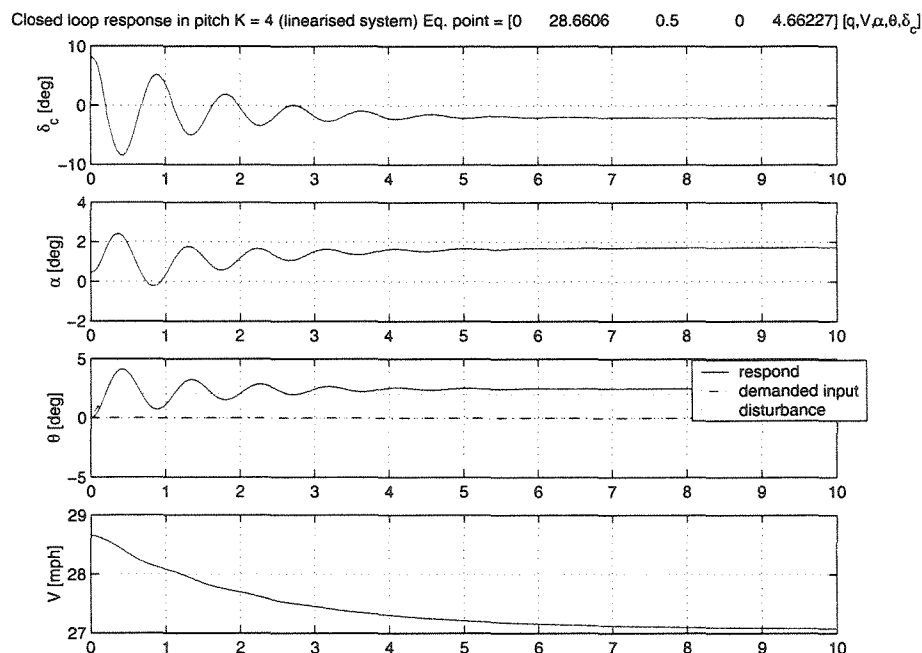


FIGURE 28. Closed loop (piloted) time response of the 1903 *Flyer* to a step command of pitch angle.

An interesting and important result, first realized during a project carried out at the Air Force Test Pilot School<sup>[27]</sup> is that the simultaneous instabilities in the longitudinal and lateral motions is particularly troublesome. This experience is partly due to the substantial difference in doubling times and partly to the pilots of modern aircraft never are concerned with unstable spiral modes having such short doubling times.

In the case of the 1903 *Flyer*, the task of controlling the rapid pitch instability tends to divert attention from preventing the divergence in roll which in fact also happens quite quickly, doubling in two seconds. Some understanding of the simultaneous instabilities is probably helpful in preparation to fly a replica of the 1903 *Flyer*.

## 5. Flight Mechanics of Wright Aircraft After 1903

In 1904, the Wrights continued flight tests of the 1903 design essentially unchanged but with slightly more power. Their results convinced them that they must make some changes. Culick<sup>[26]</sup> has given a summary of the process leading to the 1905 aircraft that the Wrights considered to be a ‘practical’ aircraft (Figure 14). They made their first public flights in 1909 using aircraft slightly modified from the 1905 design. Finally, in 1910 the Brothers adopted the conventional aft horizontal tail and at last had an aircraft stable in pitch and at most weakly unstable laterally.

During the period 1903–1912 the Wrights made almost no changes to the basic biplane cell. Most importantly, they did not modify the airfoil significantly, so their aircraft continued to possess the large nose-down zero lift pitching moment due to the wing, the origin of their difficulties with the pitch instability. The chief modifications from 1903 to 1912 were therefore the power of the propulsion system; the size and location of the vertical tail; the size and location of the center of mass. We can only guess the last, which in

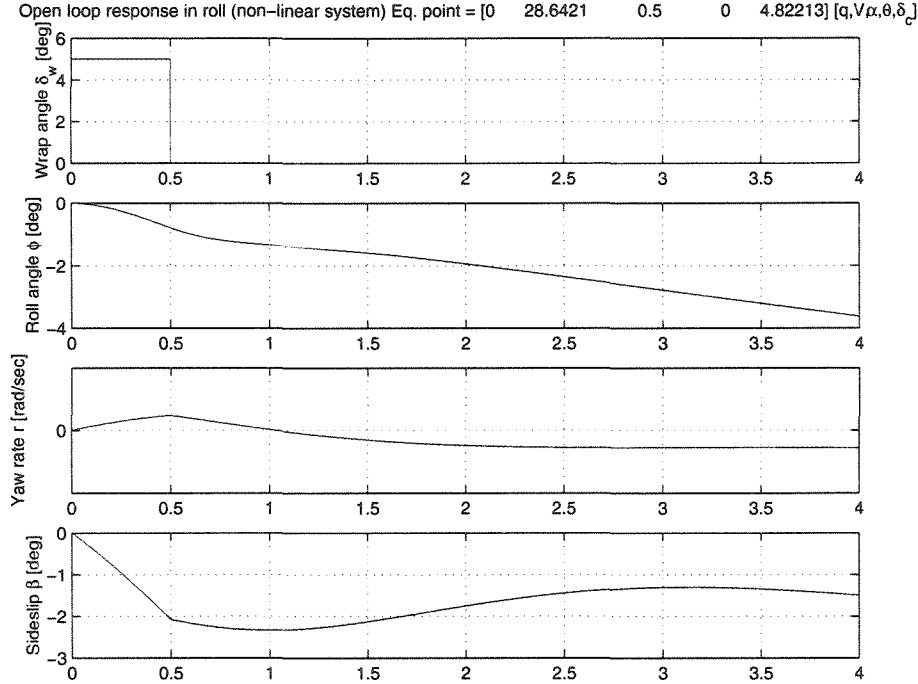


FIGURE 29. Open-loop response (fixed controls) to a square pulse change of warp angle.

the context here implies we have some unknown uncertainties in our calculated stability margins. Since we will be concerned here with dynamics of motions in steady level flight, we need not be concerned with details of the propulsion system. Thus our analysis is based entirely of matters of geometry and inertial properties. The latter also are not documented well so their values also carry uncertainties which affect mainly the frequencies of motions. We must also estimate some of the aerodynamic derivatives, including all of the rotary derivatives. Throughout we have used elementary strip theory. We will document the procedures and results in a later publication.

We have measured the geometrical characteristics of the aircraft by scaling from the drawings in McFarland's collection<sup>[4]</sup>. The results for the biplane wing are tabulated in Table 5.1 and for the biplane canard in Table 5.2.

TABLE 5.1. Properties for the Biplane Wing

Aircraft	b (ft)	S (ft <sup>2</sup> )	$\bar{c}$ (ft)	h (ft)	AR
1903-1904	40.33	510	6.5	6.17	6.38
1905	40.5	503	6.5	5.18	6.52
1907-1909	41	510	6.5	6	6.59
1909	36.5	415	5.83	5	6.42
1910-1911 Model B	39	500	6.5	5.33	6.084
1912 Model C	38	440	6	5	6.564

The gap between the biplane surfaces is  $h$ ; all other symbols maintain standard definitions. Entries for 1907–1909 machines are typical of the values for about seven aircraft built in that period. They are probably close to those for the aircraft Wilbur flew in France in 1909. The 1909 machine is a single version built as a demonstrator for the Army Signal Corps, flown by Orville at Fort Myer.

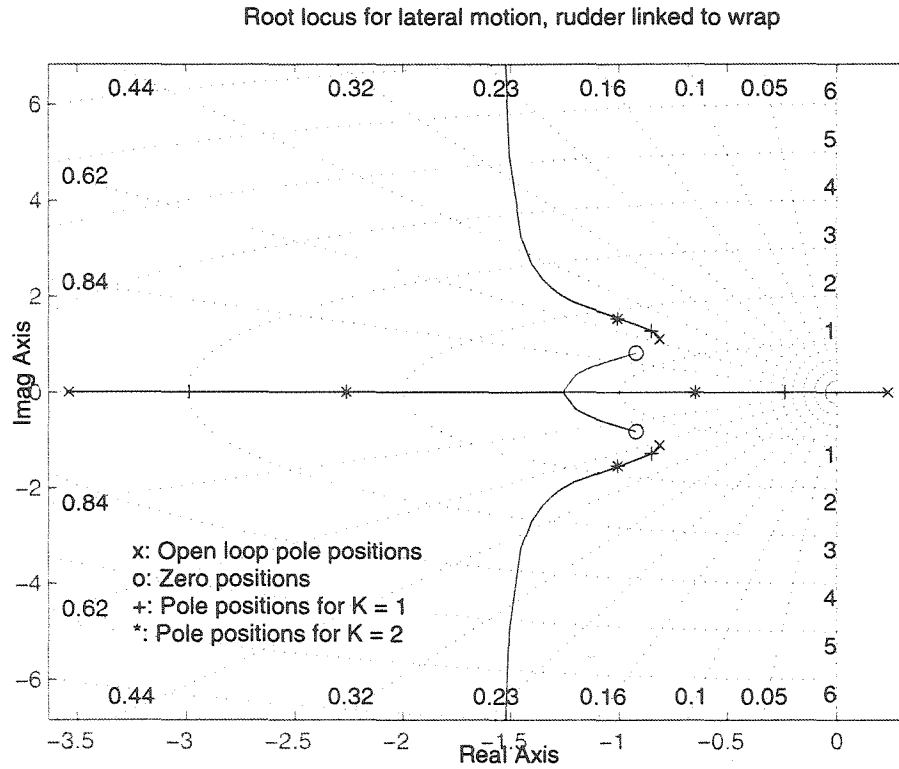


FIGURE 30. Locus of dynamic roots for lateral motions with linked warp and rudder.

TABLE 5.2. Properties of the Biplane Canard

Aircraft	b (ft)	S (ft <sup>2</sup> )	$\bar{c}$ (ft)	h (ft)	AR
1903-1904	12	51.6	2.54	2.09	5.58
1905	15.25	78	3.05	2.95	5.96
1907-1909	14.47	53.5	2.27	2.58	7.83
1909	14.3	77	3	3.0	5.31
1910-1911 Model B	19.2	38	3	5.33	9.7
1912 Model C	18.33	36	3	5	9.34

Calculations of the position of the neutral point are done in the standard fashion, determining the location of the center of mass for which the slope of the moment curve vanishes. Table 5.3 is a summary of results calculated for the neutral point and the static margin, with Hooven's estimates<sup>[29]</sup> for the center of mass where applicable.

Figure 32 is a graphical summary of the centers of mass and neutral points for the aircraft considered here. The numbers above the symbols are the values of the static margin in percent of chord.

These results show the obvious conclusion that all the Wrights' canard aircraft were seriously unstable, in fact become worse with time, contrary to their belief that the machines were improving. The resolution to this apparent paradox follows from the values of the derivative  $C_{mq}$ , the damping-in-pitch shown in Figure

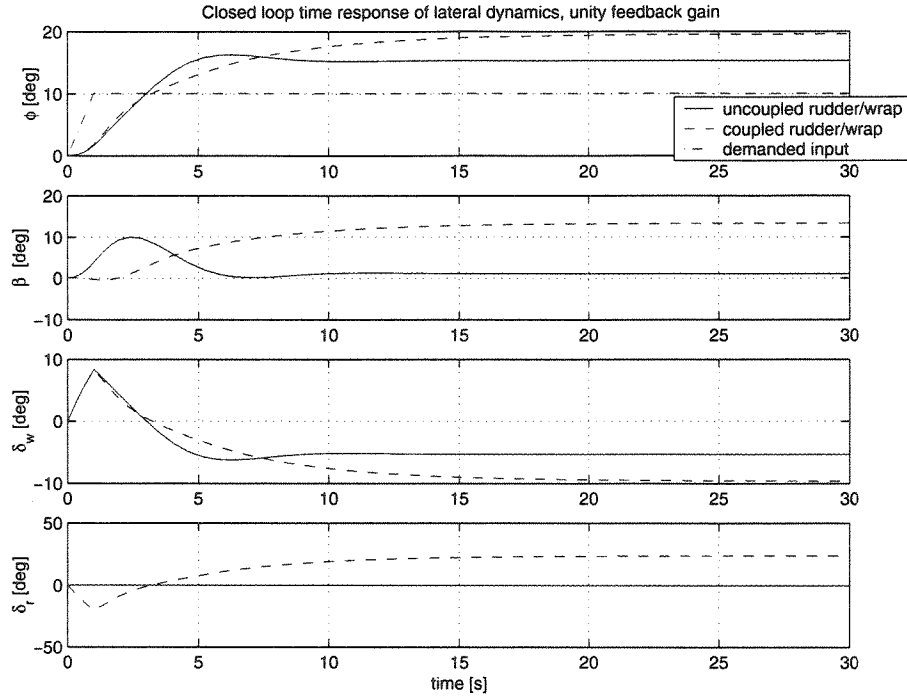


FIGURE 31. Closed loop (piloted) to a step input of warp. Results for linked and unlinked rudder are shown.

TABLE 5.3. Computed Results for the Neutral Points and Static Margins

Aircraft	$S_c$ (ft)	$S_w$ (ft <sup>2</sup> )	$\bar{c}$ (ft)	CG	NP
1903-1904	51.6	510	6.5	-29.7	-3.9
1905	83	503	6.5	-12.8	14.6
1907-1909	70	510	6.5	-15.3	12.4
1909	80	415	5.83	-14.0	18.4
1910-1911 Model B	40	500	6.5	-27.5	-41.5
1912 Model C	36	440	6	-27.5	-42.42

33. The significant increases of  $C_{mq}$  from 1904 to 1909 explain the substantially improved handling qualities of the canards.

That the damping-in-pitch is such a crucial property of the aircraft is easily understood by examining the locations of open-loop roots, Figure 36. The doubling times for the pitch instability are all less than half of the 1903 *Flyer*. Nevertheless as a film of flights in 1909 (Wilbur flying in Italy) shows, the last canard aircraft always showed its instability, and required continuous exercise of control by the pilot.

## 6. Concluding Remarks

The series of Wright aircraft from 1903 to 1912 offer a unique opportunity to examine and appreciate several fundamental aspects of the basic flight mechanics of aircraft. Owing to their insistence on retaining their canard design, the Wrights had unstable airplanes until 1910 when largely external pressures from

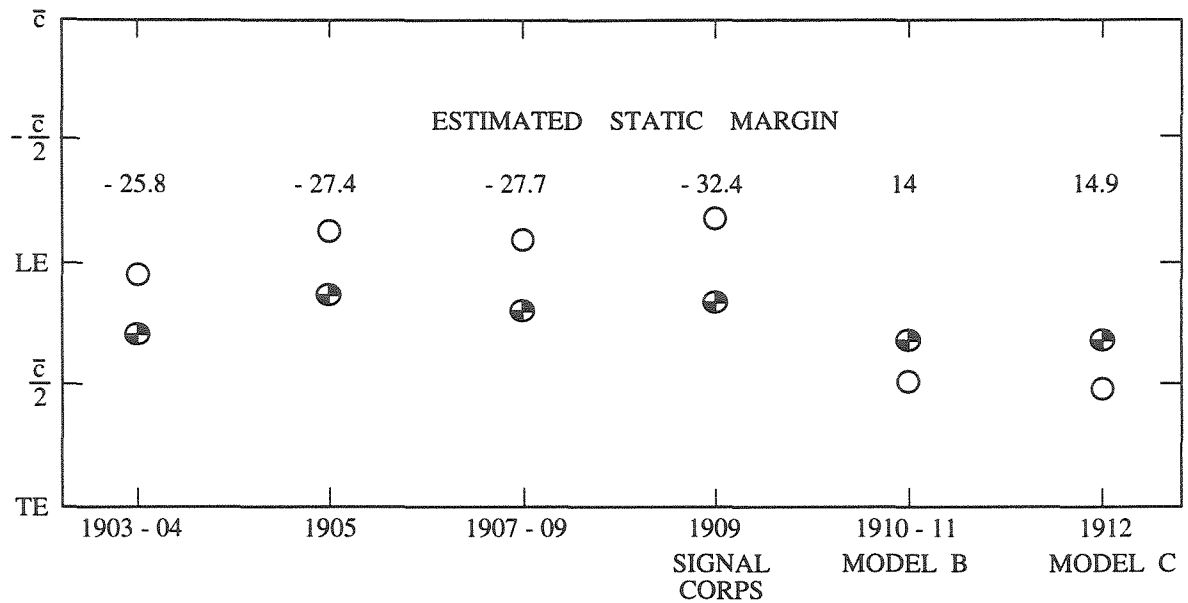


FIGURE 32. Locations of the Center of Mass and Neutral Points for the Wright Aircraft 1903-1912

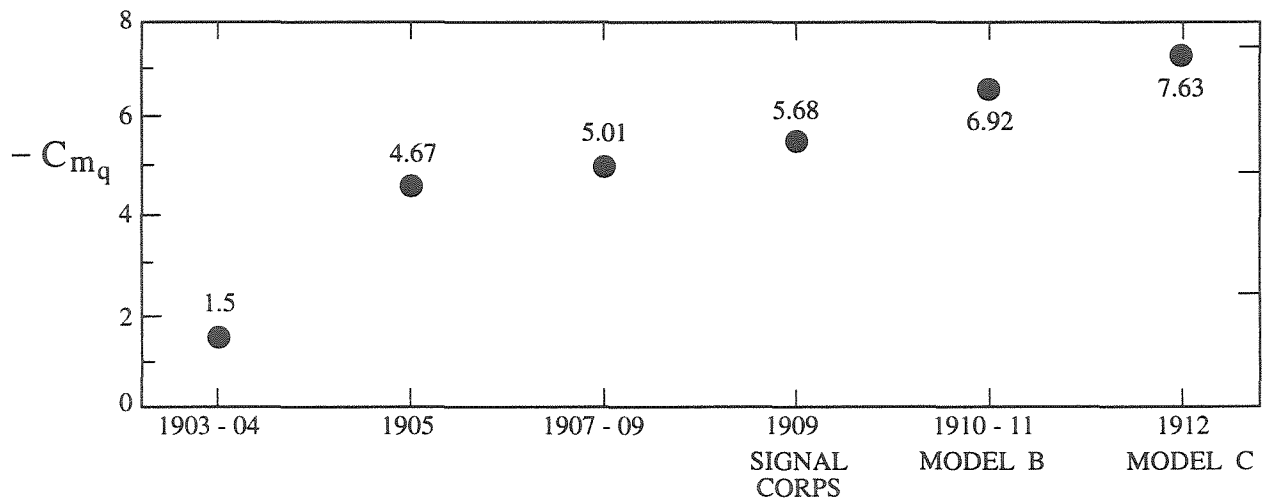


FIGURE 33. Values of the Damping-in-Pitch for the Wright Aircraft 1903-1912

competitors forced them to use a conventional aft tail. Their 1903 *Flyer* was very much the worst of the lot. Not only did it possess an instability in pitch having doubling time about one-half second, but, owing to negative dihedral, its spiral mode was unstable as well, with doubling time approximately two seconds. Analysis and simulations have shown that the aircraft was certainly flyable by a reasonably skilled pilot, particularly if the workload was reduced by linking the warp and rudder, as the Wrights chose to do in 1903. However, coping with the two independent instabilities simultaneously is a difficult task. Too much concentration on the pitch instability ( $\tau \sim 0.05s$ ) means that control of the spiral instability ( $\tau \sim 2s$ ) will be lost. The limited control authority in both pitch and roll makes the problem worse.

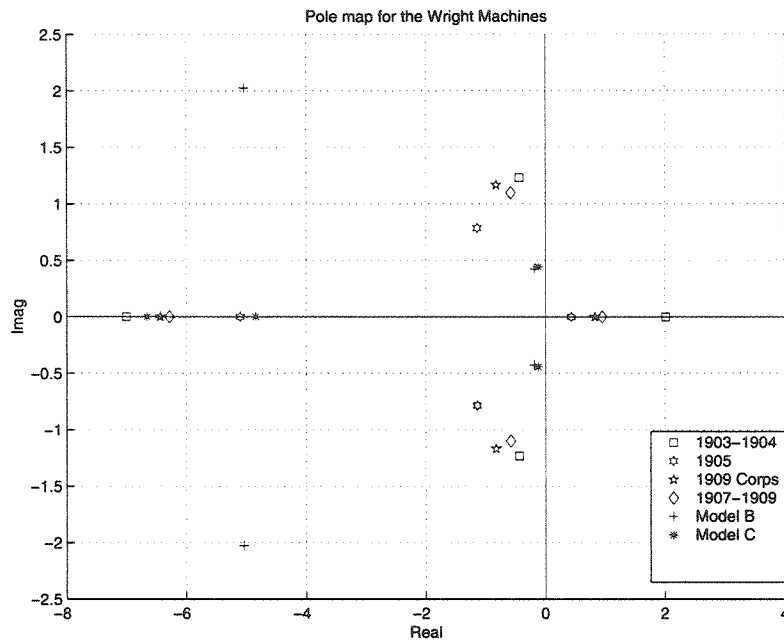


FIGURE 34. Migration of roots for longitudinal motions, 1903–1912

During their test flights in 1904, with the 1903 configuration but somewhat more power, the Wrights discovered their problem with lateral motions. They removed the negative dihedral which had been installed in 1902 to solve an annoying problem they had experienced when gliding downhill in gusty conditions. It had served a purpose then but of course made turning under power dangerous and nearly impossible. Increased volume of the vertical tail in 1905 gave the improved directional stability and control in yaw necessary to execute successful turns. For reasons they didn't explain clearly, the Wrights also added 'blinkers,' fixed small vertical surfaces forward of the wings. Those additions increased damping in yaw, at the expense of reduced directional stability. Their action differs from that of the all-moveable vertical tail in the respect that they did not participate in control.

During their two years of development, 1904–05, as well as in the period 1908–1910, when they were trying to sell their aircraft, the Brothers were continuously battling the problem of pitch instability. Their solution consisted of two changes: move the center of mass forward by adding ballast to the canard; and increase the volume of the canard both by increasing its area and moving it forward. The static stability is improved by the first and reduced by the second. Thus our current estimates suggest that the static margin of the canard aircraft really didn't change much from 1903–1909, remaining around  $-25\%$ . What the revisions of the canard really did helpfully was increase the damping-in-pitch, with considerable improvement in the handling qualities of the aircraft. Not only were the pitching motions more heavily damped, but the doubling time of the pitch instability was itself doubled to about one second in 1909. Thus the major improvements in the canard aircraft from 1903 to 1909 were elimination of the lateral instability and improved controllability of the pitch instability. With the increased power available the airplane therefore became, so far as the Wrights were concerned, perfectly acceptable as a practical machine.

Others disagreed, and their aircraft proved superior to the Wrights' machines. So finally in 1910–1912 the Brothers adopted the aft horizontal tail and produced an aircraft without instabilities. Although intrinsically stable canards can be built, the Wrights' design posed two insurmountable problems: in its designed form,

90% or more of the total weight is in the biplane cell. Hence a very substantial part of that mass must be added as ballast to the canard to give a positive static margin. Then to trim the airplane with such a large amount of weight forward requires the canard to carry a large loading, marginally possible with the airfoils known to the Wrights.

The second problem, which the Wrights never recognized<sup>[10,26]</sup>, was the large (nose-down) zero-lift pitching moment of the airfoil. A suitably changed profile—e.g., much reduced camber, or reflexed trailing edge—will eliminate the pitch instability. With such a modification, the Wrights' canard might well have competed successfully with contemporary conventional configurations and aircraft generally might have looked differently for a few years!





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